A review of the current status, scope and future trends for MEMS technologies

The 21st International Battery Seminar and Exhibit

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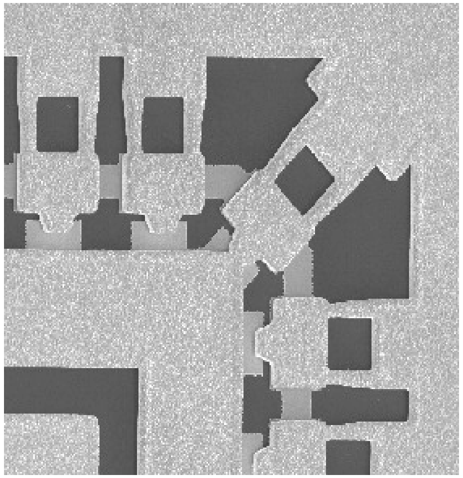
Agenda

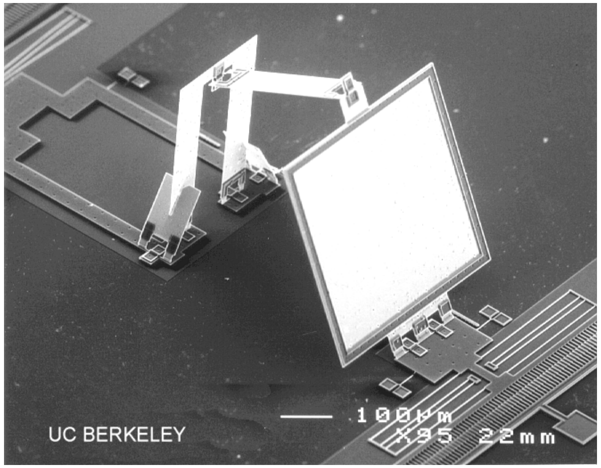
- Introduction to MEMS
- MEMS technology
- MEMS relevance to micro fuel cells
- Applications of MEMS
- Conclusion

What is MEMS ?

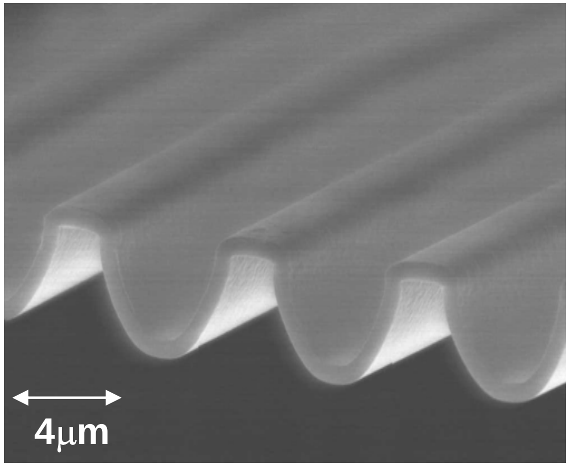
- Micro-Electro Mechanical Systems
  - 3D structures – with microns sized lateral dimensions
  - Add mechanical sensing and movement/actuation to electronics
  - Fabricated using IC-compatible batch-processing techniques
- Also known as “*micromachines*” (in Japan), or “*Micro Systems Technology*”, or “*MST*” (in Europe)
- A Micro-System is the integration different technologies into a single module
  - MEMS, CMOS, Optical, Fluidics etc into a single module



Intel RF switches

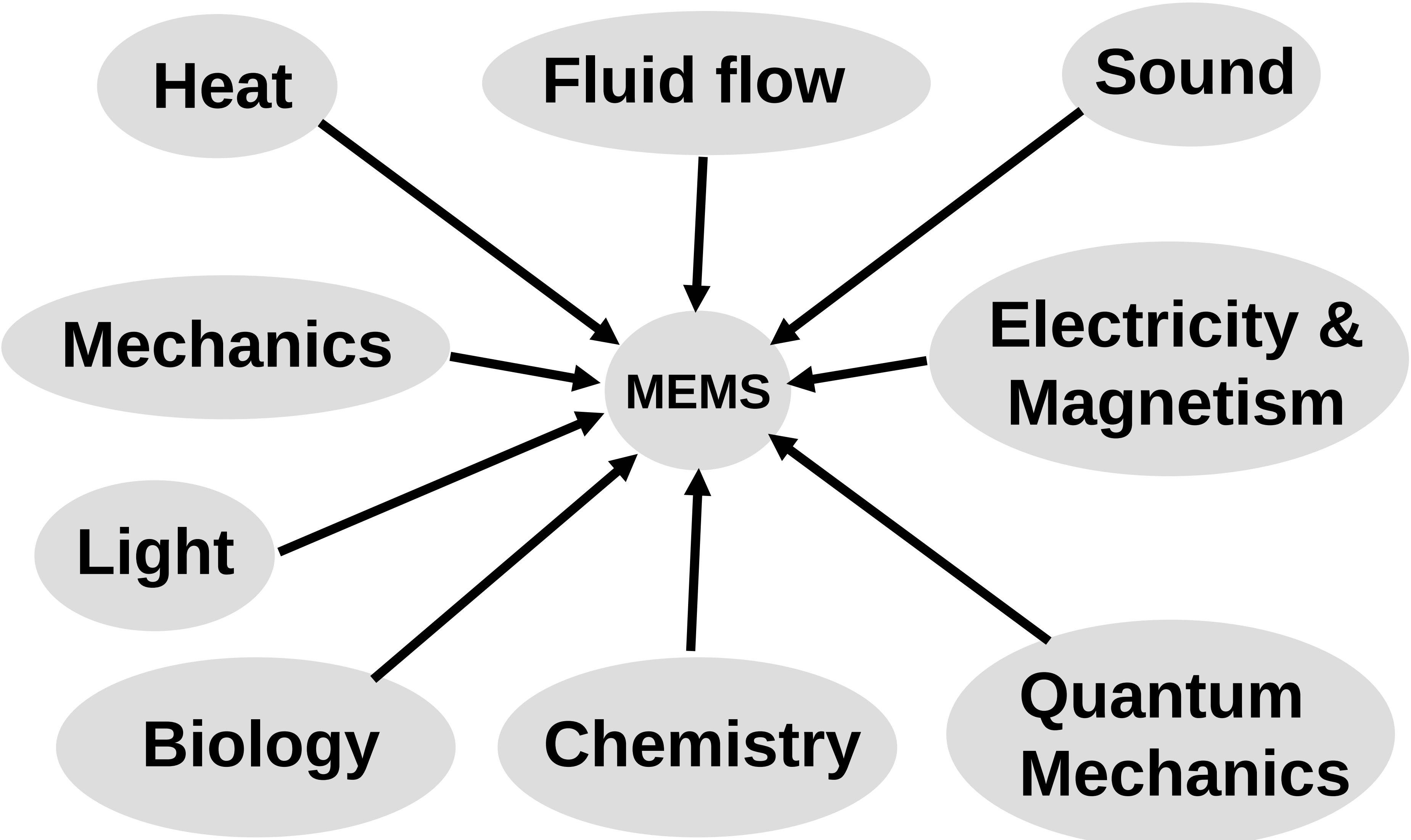


Credit UC Berkeley – BSAC



Intel Micro-spring

Another way of looking at MEMS – linking different science domains



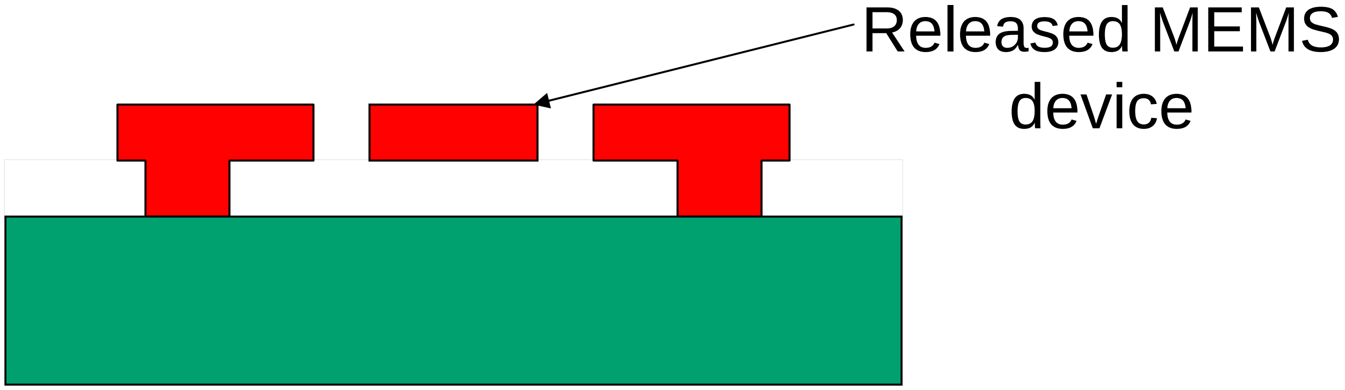
Some applications for MEMS

Applications		
Pressure Sensor Accelerometer Print Heads Micro Gyro	←	**Better Faster Cheaper**
Displays Biochips Wireless Chip Cooling Optical Switch Tunable Laser Mass Storage Micro Fuel Cells	←	**Brave New World of MEMS**

Any application that involves 3-D micro-systems benefits from the silicon batch fabrication that MEMS provides

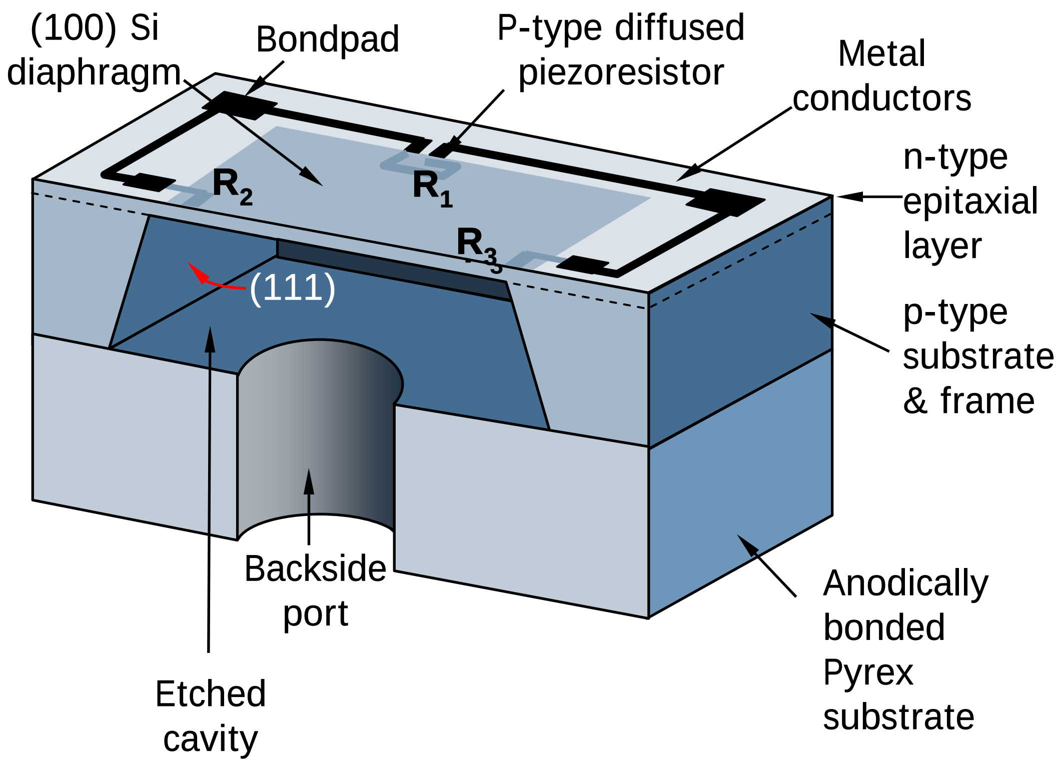
Surface Micromachining

- Definition: MEMS that are made using films deposited on a wafer, like CMOS
  - The structural layer has the desired mechanical, electrical, and thermal properties, etc.
  - The sacrificial layer supports the structural layer until it is etched – the “release etch”

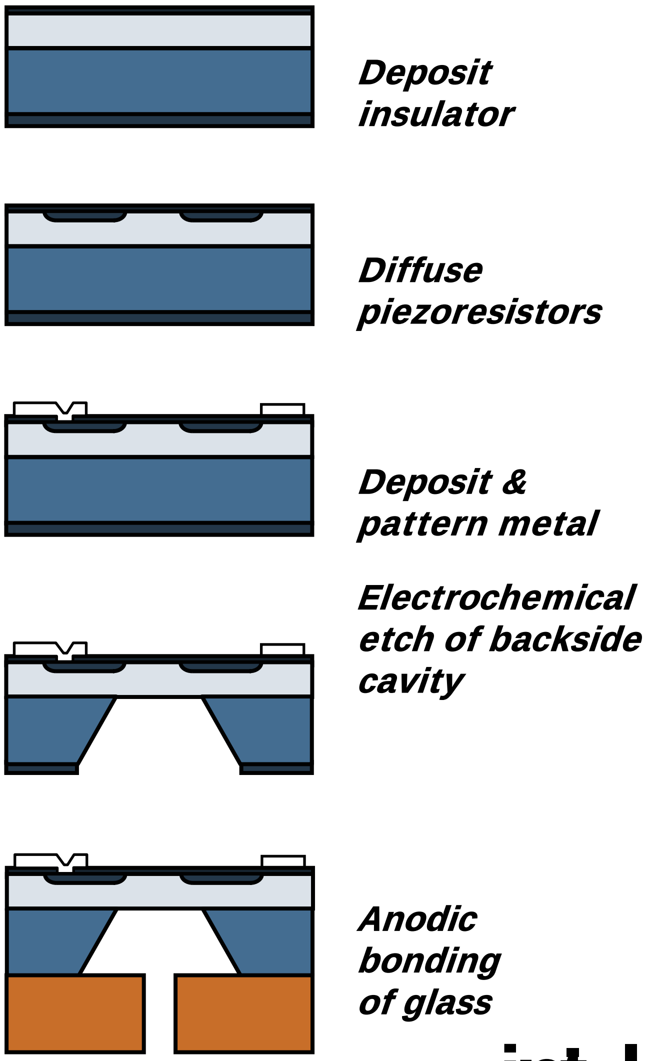


Bulk Micromachining

Silicon is sculpted to the desired shape with VLSI etching methods

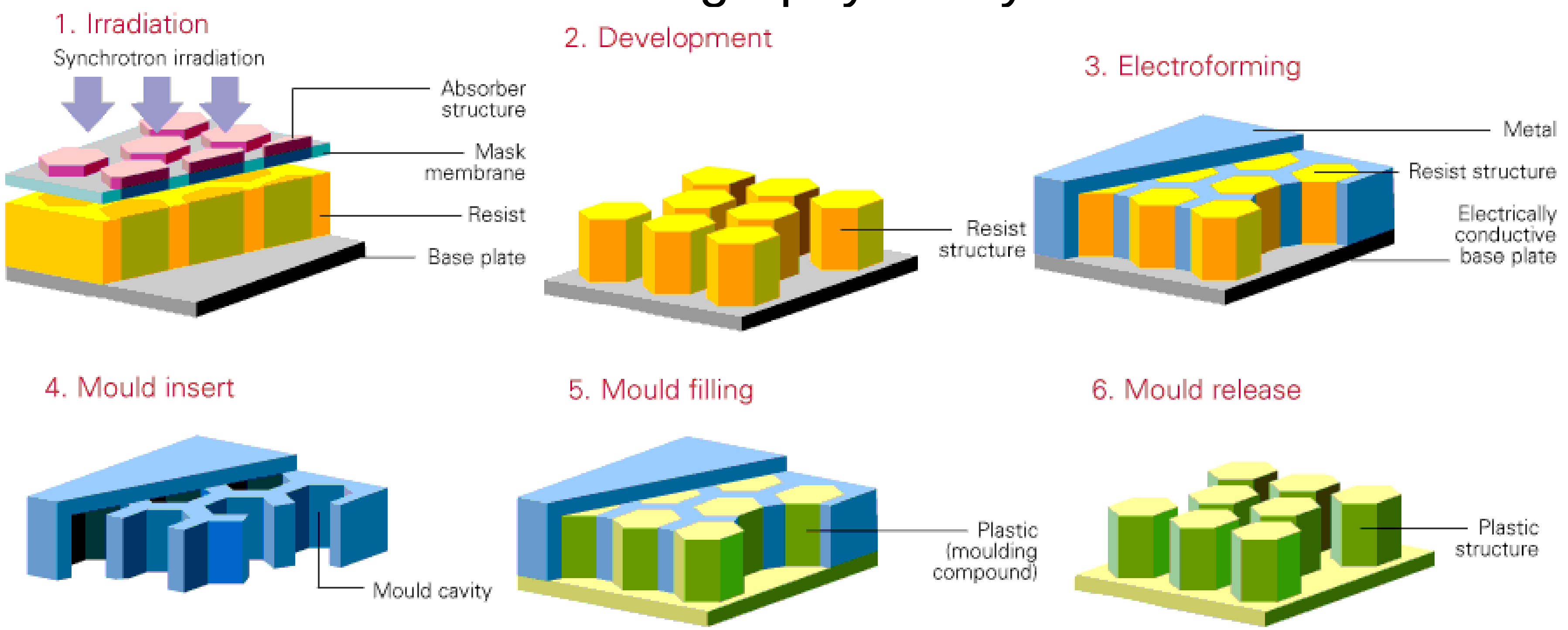


Bulk Micromachined Pressure Sensor



LIGA

- **<u>LI</u>**GA - **<u>Lithography</u>** **<u>G</u>**alvanoformung [Electroplating] **<u>A</u>**bformung [Injection Molding]
  - Used to make very high aspect ratio micro molds that can be used for high volume manufacture
  - High aspect ratio lithography is key for LIGA



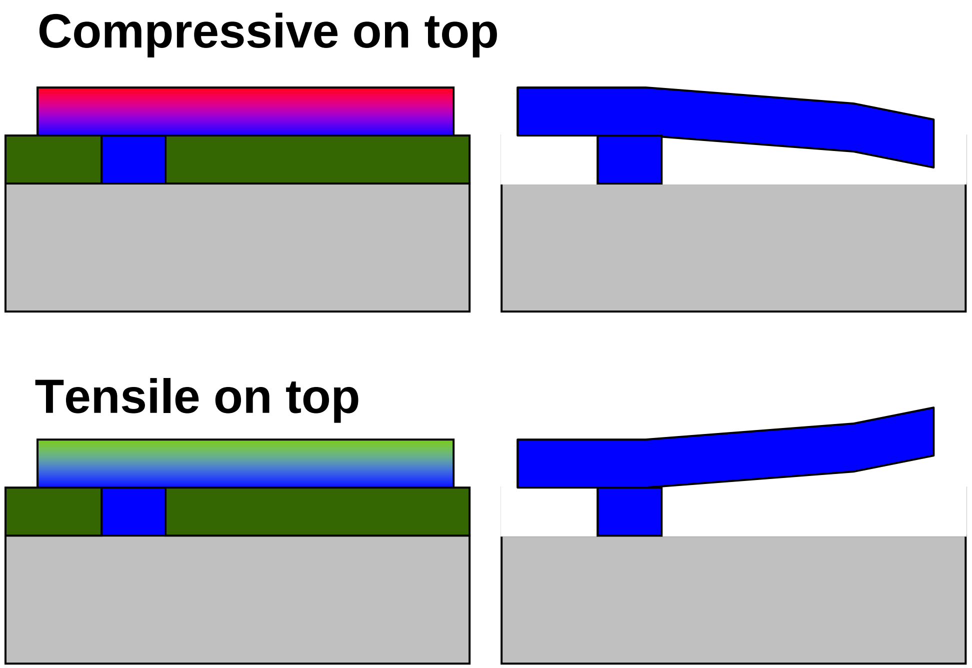
Picture Courtesy of Dr Bill Tang DARPA

What differentiates MEMS from CMOS

- MEMS processing is backend (no transistors)
- Extensive use of ***silicon micromachining***
  - Very high aspect ratios
  - Use silicon as the material of choice for “sculpting” with the precision of semiconductor fabrication
  - High precision in the Z direction (perpendicular to wafer)
- Extensive use of new materials and thick electroplating:
  - Nickel, gold, polymers such as PDMS, Hydrogels
  - Requires a mix and match processing between a VLSI clean room and special areas for processing with contaminating materials
- Extensive use of multi wafer bonding:
  - Breakdown the complexity of a 3-D structure to multiple wafers followed by alignment and wafer to wafer bonding
- Packaging is an integral part of MEMS manufacturing

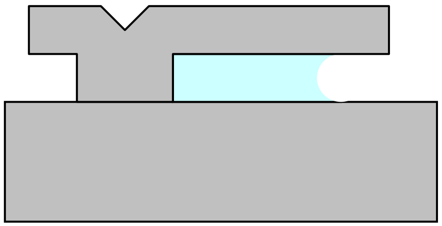
MEMS challenges: Stress gradients

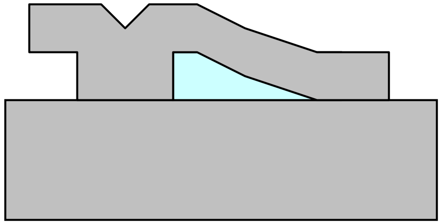
- A stress gradient is a difference in stress between the top and the bottom layers of a film.
- If the film is more **<u>compressive</u>** on top than on the bottom, the film curls down;
- If the film is more **<u>tensile</u>** on top than on the bottom, the film curls up.

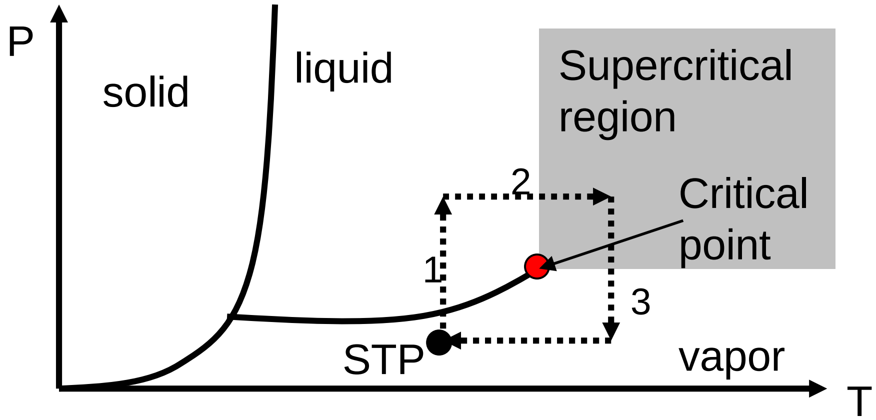


Releasing MEMS: The Stiction Problem

- The problem:
  - Surface forces (van der Waals, hydrogen bonding, etc.) are much stronger than bulk forces (spring restoring forces, gravity)
  - The meniscus that forms during drying pulls structures into contact
- The result:
  - MEMS stick upon contact
  - Common for MEMS that are mechanically compliant (e.g. varactor) or have small gaps (e.g. beam resonator)
- Solutions:
  - Avoid the meniscus by drying MEMS in supercritical CO_2, where liquid and gas phases are indistinguishable
  - Release etch with acid vapor or plasma
  - Coat surfaces with anti-stiction films

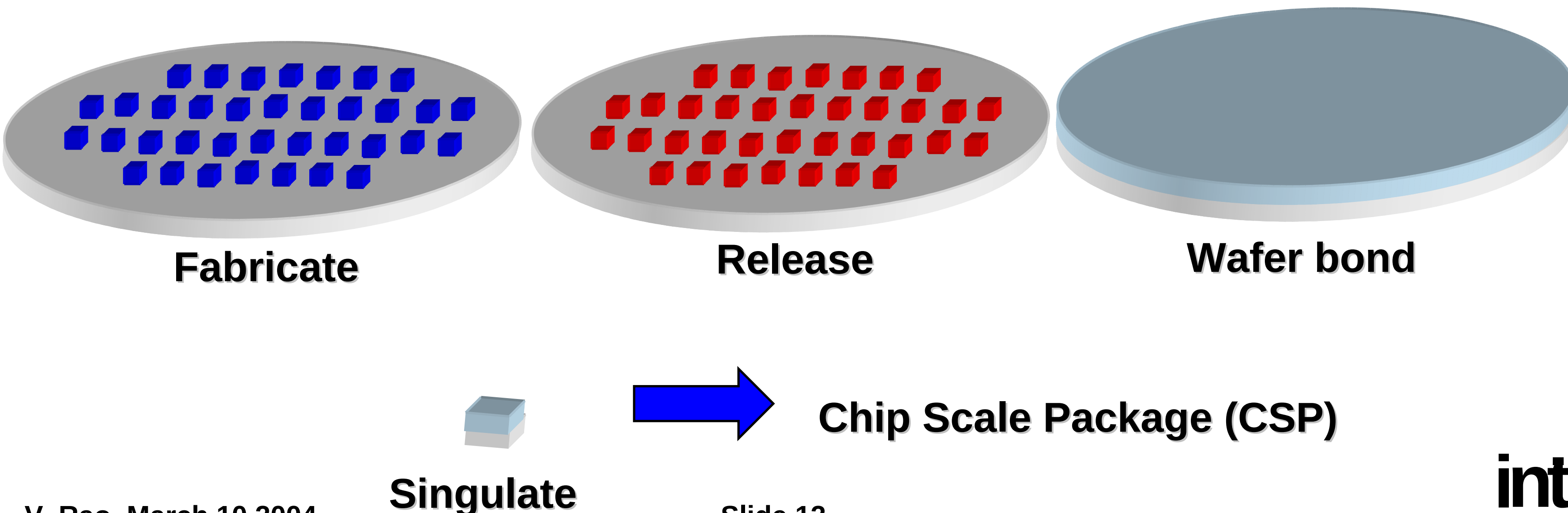




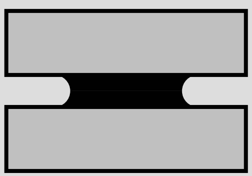
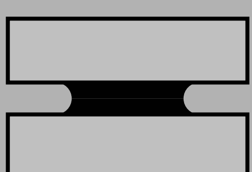


Wafer Level Packaging

- After release, the fragile MEMS devices must be protected from dicing and handling:
  - The devices must be packaged immediately after they are released to prevent particles, stiction etc
  - Packaging must be hermetic
- Wafer level release followed by wafer level bonding is best approach to accomplish this at lowest cost



Wafer Bonding Methods

Techniques		Advantages	Drawbacks
“Surface” bonding		Hermetic	Flat surface required
	Anodic	strong bond	high-voltage
	Fusion (Direct)	strong bond	high temp
	Surface-activated	varies	varies
Metallic interlayer		Hermetic Non-flat surface ok	Specific metals required
	Eutectic	strong bond	flat surface required
	Thermocompression	non-flat surface ok	high force
	Solder	self-aligning	solder flow possible
Insulating interlayer		Non-flat surface ok	Varies
	Glass frit	hermetic common in MEMS	large area medium-hi temp
	Adhesive	versatile	non-hermetic

MEMS reliability

- Mass of Moving structures is very low:
  - Shock is not generally a big issue
  - Resonant frequencies can be controlled by engineering the stiffness of the supports
- Classical mechanical failure modes get much better:
  - E.g plastic deformation
- Biggest issues are:
  - with surfaces that rub or impact each other
  - As devices shrink surface dominates (Surface/Volume ratio ~ $L^2/L^3 = 1/L$) and device is more susceptible to the environment
- Major failure modes for MEMS devices are in back end
  - Release stage
  - Packaging - environment has a large effect on the MEMS devices
- Reliability qualification of New types of MEMS devices needs to be addressed early in the development phase
  - Could become the bottleneck for market acceptance

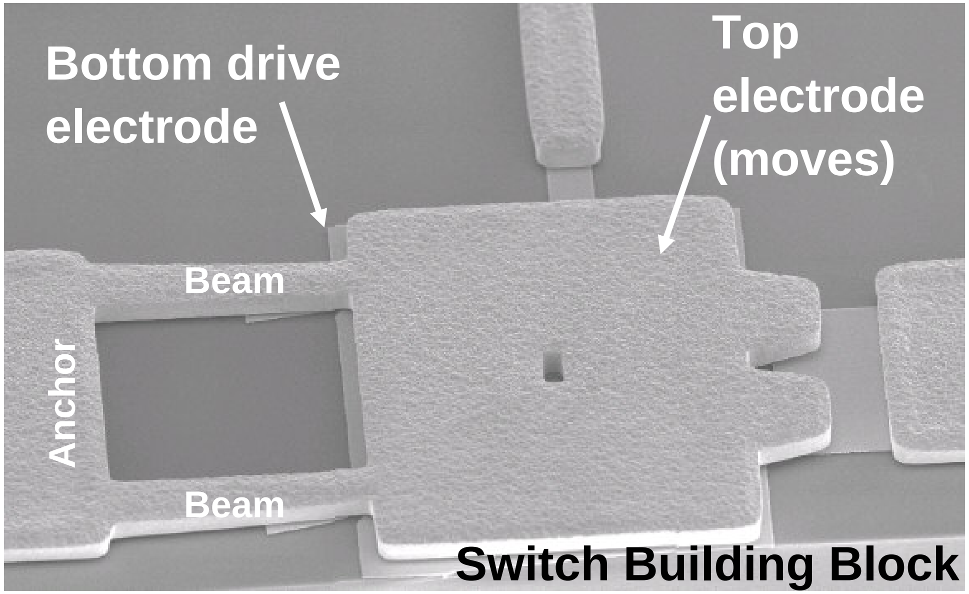
MEMS trends

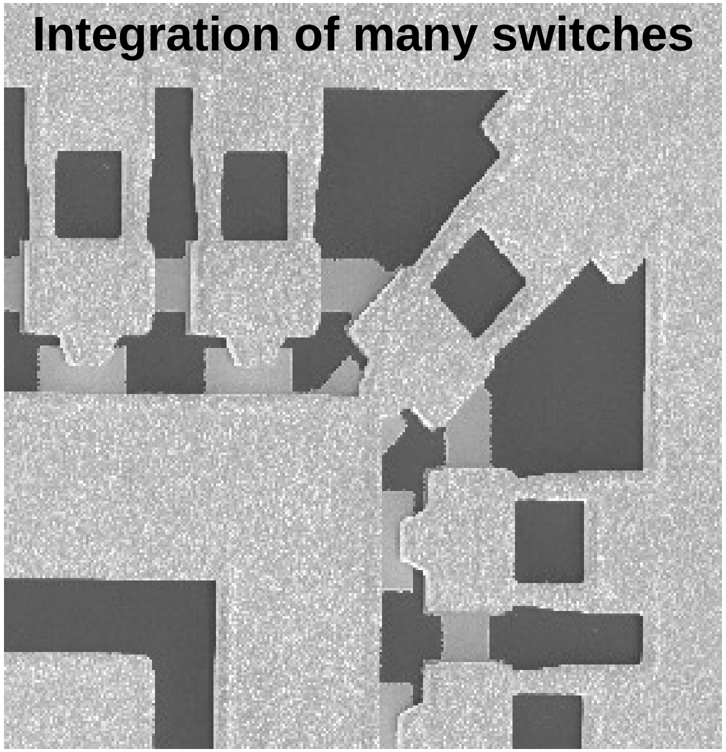
MEMS in the 1980s		MEMS in the 2000's
Purely mechanical	→	Multi physics domains
Discrete packaging	→	Wafer level packaging
Pure silicon	→	Silicon + New materials
Component focus	→	μ–systems focus
Proprietary tools	→	Vendor supported tools
Research driven	→	Cost driven

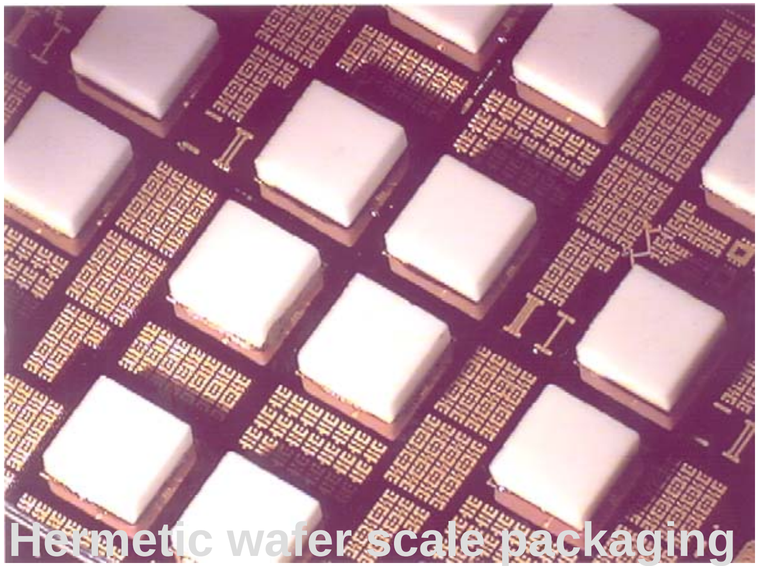
MEMS building blocks relevant for micro fuel cells

- Fuel cells are the intersection of a number of physics domains:
  - Thermodynamics, Fluid flow, Electro-chemistry
- Batch processing on silicon wafers
  - Utilize the significant industry wide expertise in processing silicon to achieve lower cost
- Silicon micromachining for creating micro-fluidic channels (fuel and gas delivery)
- Multi wafer bonding to create complex 3-D stacks
- Miniature pumps and valves
  - Silicon + polymers such as PDMS, Hydro-gels, Parylene
  - Polymers provide compliance and the ability to seal for valves and pumps
- Deposition of thin films of exotic materials using semiconductor techniques
  - New electrode materials
  - New types of electrolytes, precise thickness control to maximize conductivity
- Micro Reactors as demonstrated by the MIT group for reforming hydrogen from ammonia or butane (Leonel Arana et al)
- Porous silicon electrodes which vastly increase surface area for improving performance of catalysts (Neah Power systems)
- Fuel reforming followed by Solid Oxygen Fuel cell (Lilliputian, MIT and LLNL)
- Silicon fuel reformer and MEMS stacked fuel cells as an alternative to Direct Methanol Fuel cells (Ultracell)

MEMS for RF switching



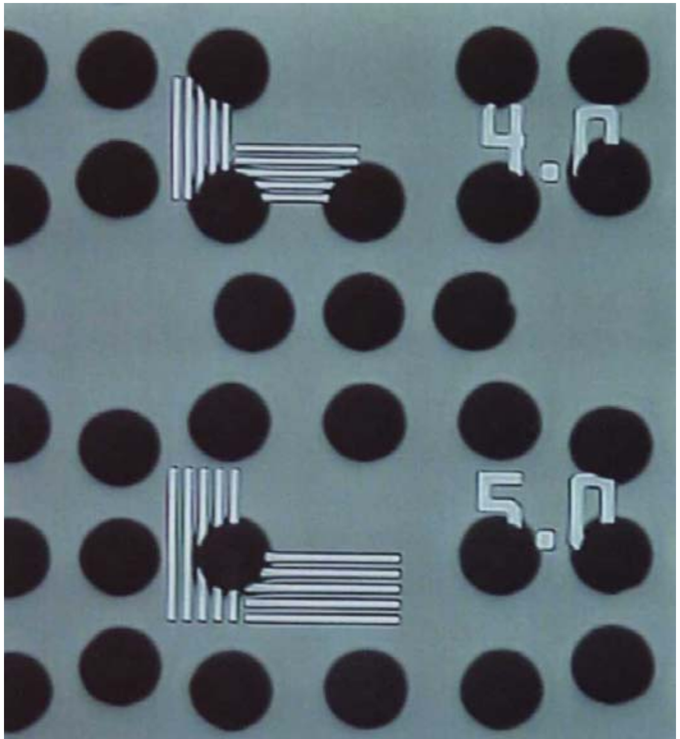


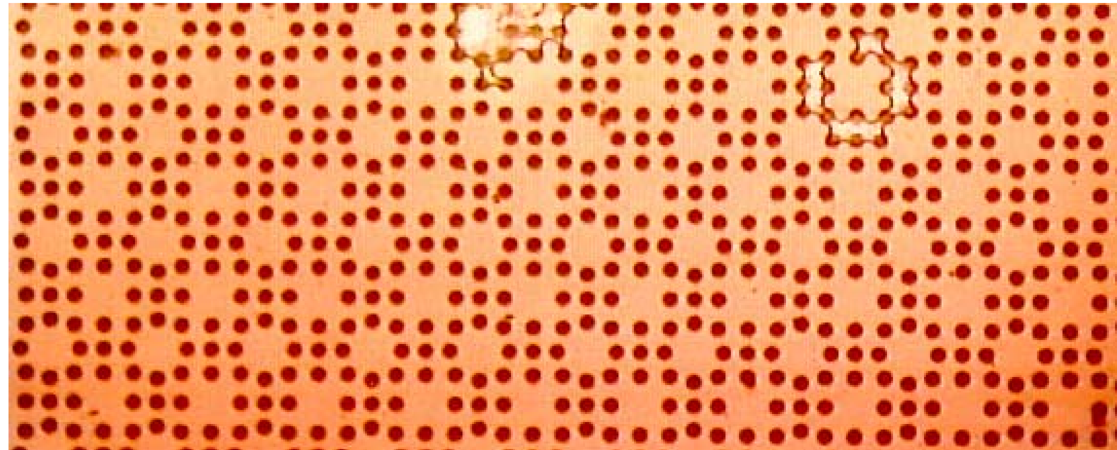


- Laterally lithography requirements are modest:
  - Mechanical devices are large10 µm -100 µm
- Vertically:
  - Layer thickness control requirement are extremely stringent: **“Nanometer sized gaps”**
  - Advanced materials with excellent mechanical and electrical properties are needed

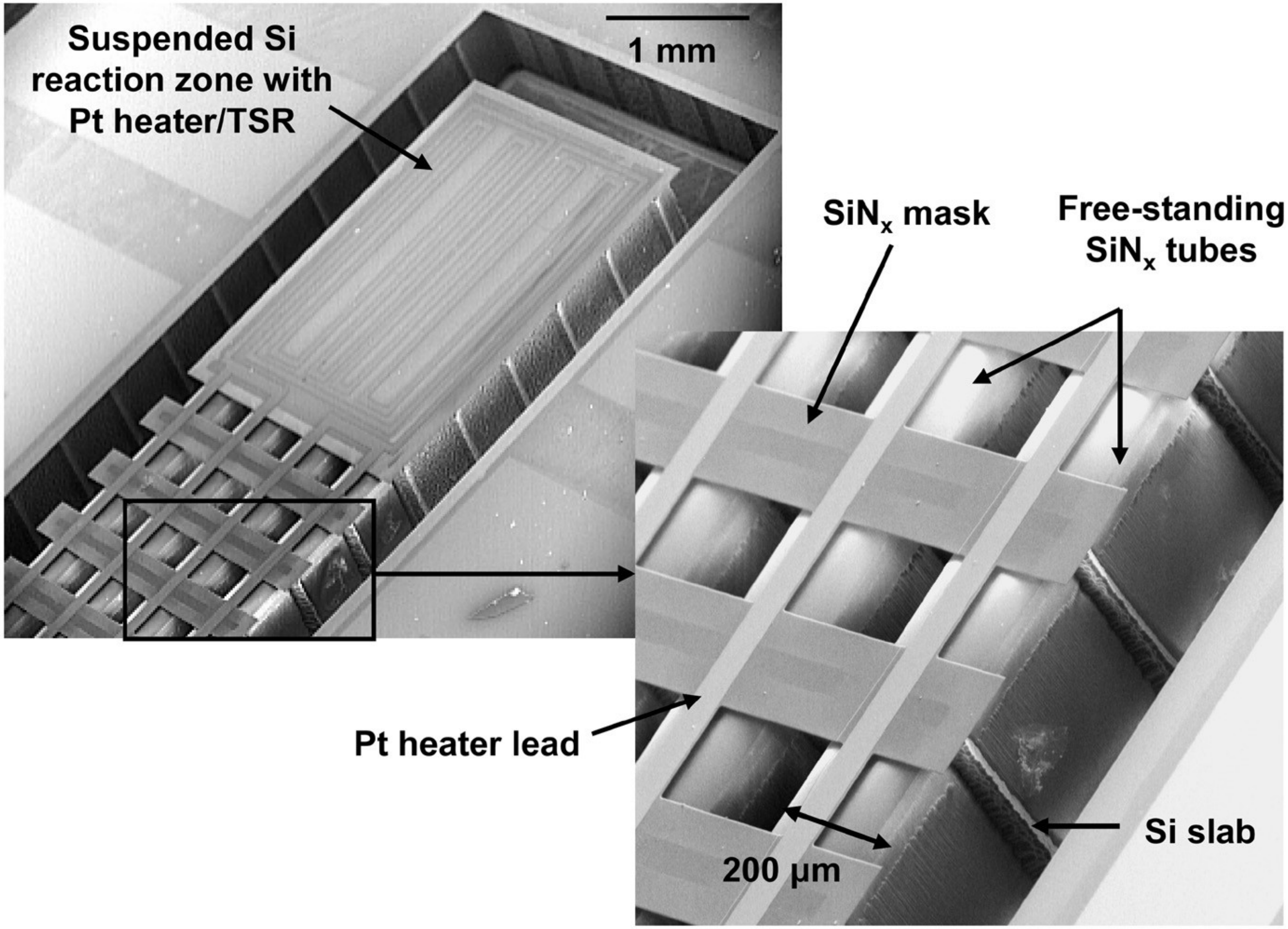
Source: Intel

High aspect ratio Silicon etching for packaging





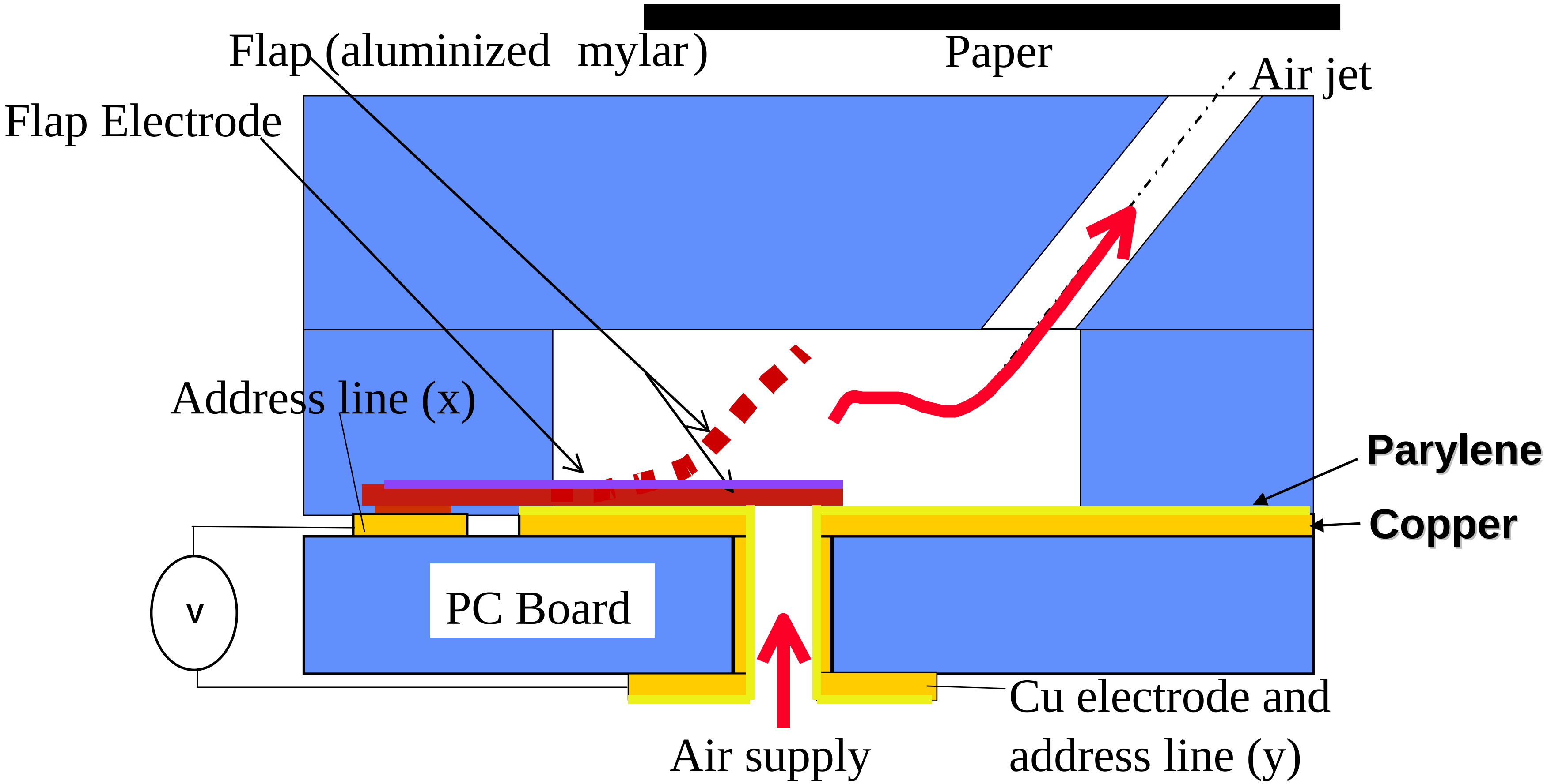
MEMS application to a micro reactor



Courtesy Leonel. R. Arana (Ph.D thesis) and K.F. Jensen & M.A. Schmidt MIT

Application of micro-machining and wafer bonding to fabricate a micro reactor for reforming hydrogen from hydrocarbon fuel

Cantilevered valve structure

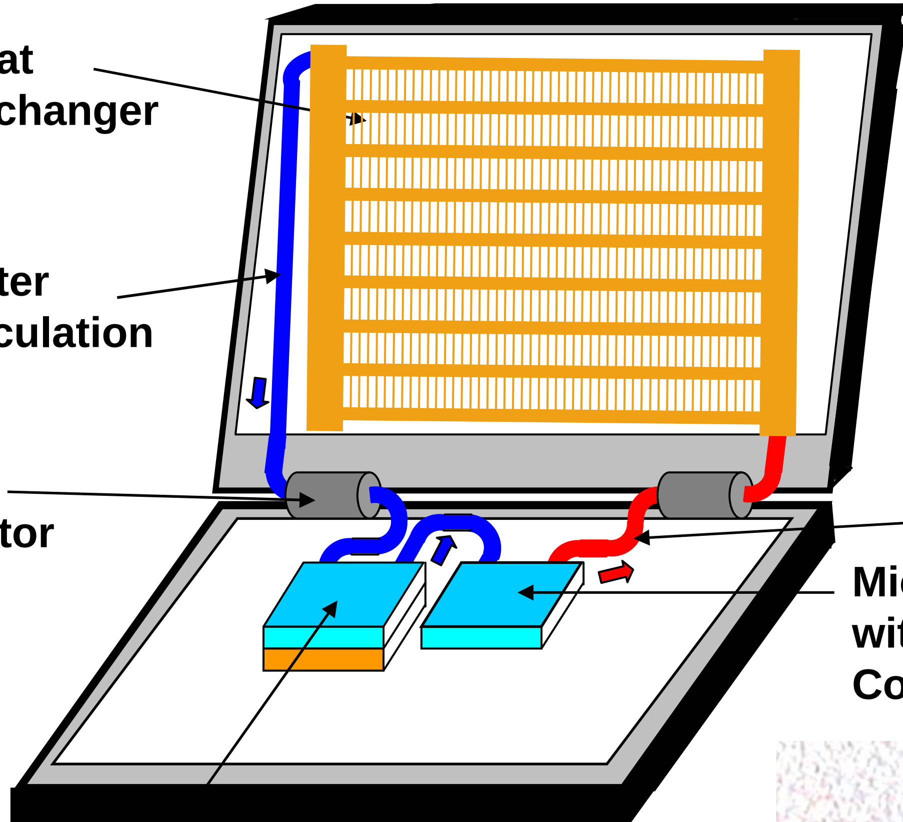


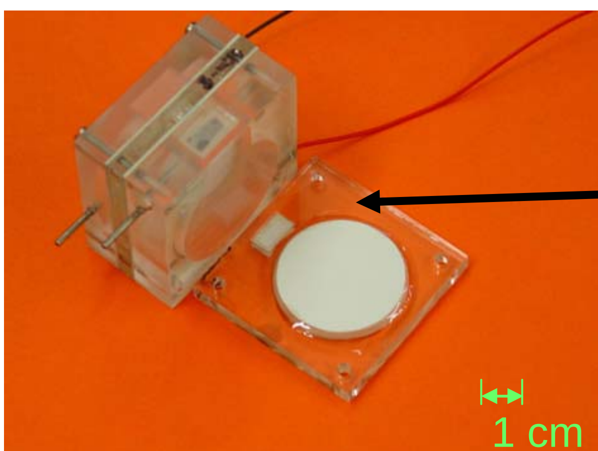
Air flow opens the valve. Electrostatic force closes it and keeps it closed. The Mylar flap closes like a "Zipper"

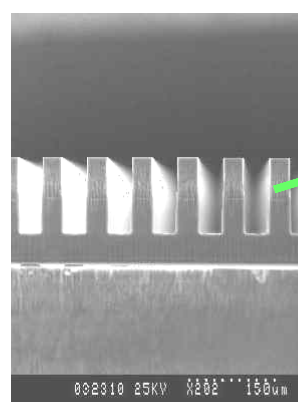
An example of a MEMS fluidic valve Courtesy of Andrew Berlin (Intel) & Xerox PARC

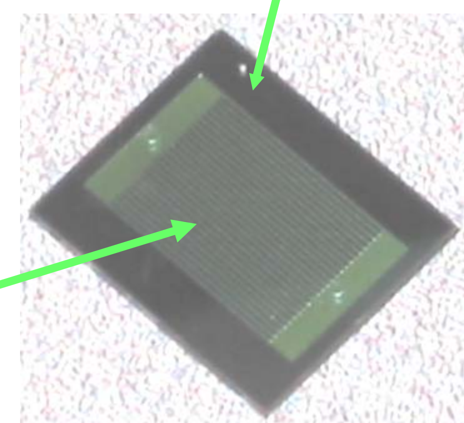
Liquid Chip Cooling for notebook computer

Research Project at Stanford Univ: Courtesy Alan Myers, Intel and Juan Santiago, Stanford

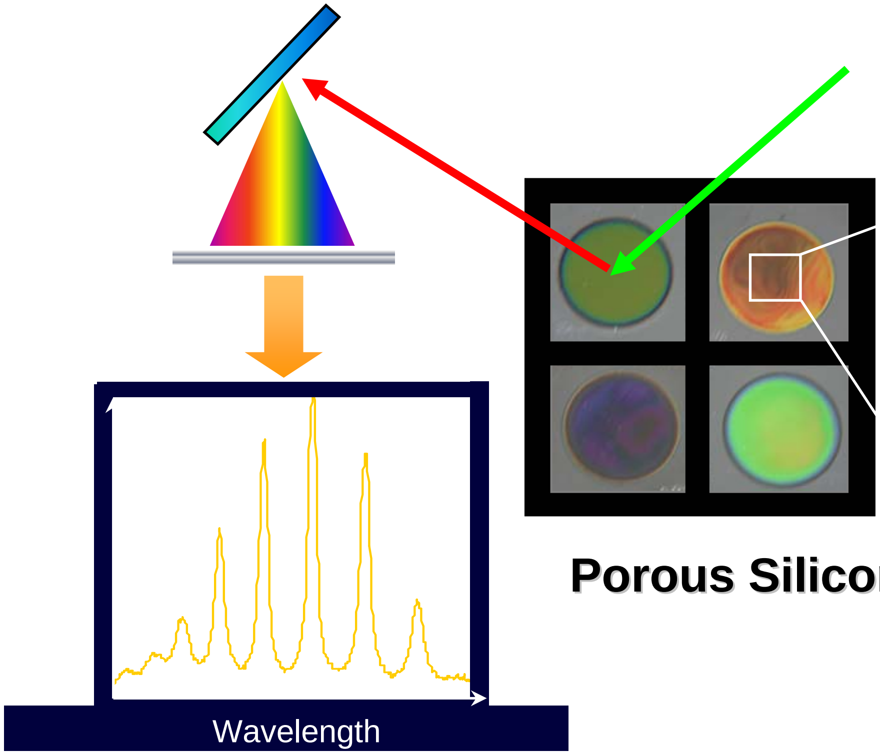




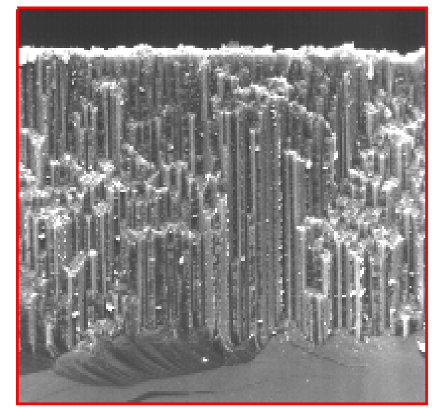




Optical Based Biosensors



Porous Silicon



Micrograph of nanopores

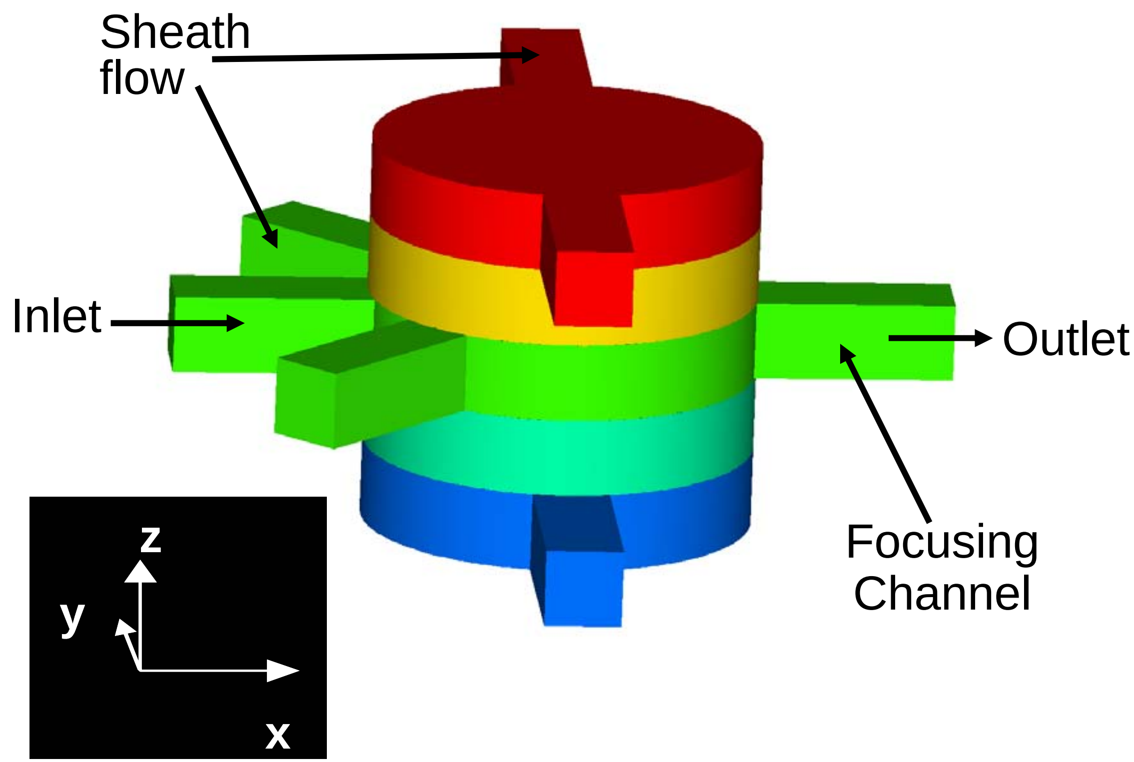
- Nanoporous silicon can be used as a large surface area matrix as well as the transducer of biomolecular interactions
- Easily integrated using microelectronics technology
- Demonstrated versatile ability to sense: DNA, Protein, Virus, and Bacteria

Source: Intel

Advanced Microfluidics

3-D 'Hydrodynamic Focusing'

- **Traditionally 2-D focusing is used in flow cytometry for:**
  - **Transport and precise positioning of molecules for detection**
  - **Keep molecules centered in flow to prevent clogging, sticking to channel walls and also to minimize optical and material interference from walls**
- **Extend to 3-D through stackup of multiple layers of PDMS**



Using PDMS layers for a 3-D micro-fluidic device

Source: Intel

** N. Sundararajan et al., Nanotech 2002.*

Conclusions

- MEMS is a ***silicon technology*** – not a product
- MEMS enables the fabrication of 3-D structures using well proven silicon micro-fabrication techniques.
- By combining CMOS processing with post processing of new materials, MEMS provides the flexibility needed to couple multiple science domains
- MEMS, in conjunction with CMOS, enables a broad spectrum of new applications such as micro fuel cells